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13. ABSTRACT (*Maximum 200 words*)

The work accomplished in this research effort has concentrated on developing models, Theoretical tools and computational algorithms for identification and control of fluid-structure interaction problems. Eleven research publications were written under the sponsorship of this grant. Titles include: "Optimal Control of Lift/Drag Ratios on a Rotating Cylindar:" "Optimal Control of Viscous Flow past a Cylinder," and "Analysis of Regularized Navier Stokes Equations".

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FINAL TECHNICAL REPORT

ON

AN UNSOLICITED PROPOSAL FOR MODELING, IDENTIFICATION, AND ACTIVE CONTROL OF FLUID DYNAMICS

GRANT AFOSR 89-0079

FOR THE PERIOD

NOVEMBER 15, 1988 - JANUARY 31, 1992

SUMMARY OF RESULTS

Flow control is a critical issue in the advanced design of aero/hydro-maneuvering vehicles which may provide the real-time effect for many important applications, such as extremely fast maneuvers for super-maneuverable aircraft, and optimum design of aerodynamic configurations. The principal developments on the problem of controlling unsteady flow so far have been essentially accomplished by experimental investigation, while the analytical as well as computational approach has received far less attention. Our efforts during the past three years have concentrated on developing models, theoretical tools and computational algorithms for identification and control of fluid-structure interaction problems. These problems are highly nonlinear and the construction of open-loop simulations are extremely complex. We are approaching these problems with the ultimate goal of building the foundation for practical control design algorithms.

Understanding of the mathematical structure of the Navier-Stokes equations is essential to may control problems in fluid dynamic systems. One major open problem is the global well-posedness of the initial boundary value problem associated with the three-dimensional (time dependent) fluid flow. In [1] and [2] we completed a study of a regularized form of the Navier-Stokes equations based on an artificial viscosity type perturbation. The regularized equations have global solutions and can be represented by a nonlinear semigroup. Moreover, it can be shown that in certain cases the regularized systems converges to the conventional Navier-Stokes system [3]. This regularized model provides a first step in developing a well-posed distributed parameter model for testing control designs.

In the area of boundary-layer control, the effectiveness of moving surfaces on an airfoil has been demonstrated by the experimental work of Modi. The boundary-layer is controlled by placing rotating cylinders at the leading and trailing edges of an airfoil. It has been shown experimentally that this mechanism can retard the initial growth of the boundary layer, with important consequences for lift enhancement and stall delay. Motivated by Modi's work, we proposed a model for the numerical study of controlling the temporal development of the flow field around a circular cylinder by employing a moving boundary control mechanism, i.e., rotating the cylinder. Much of the emphasis was placed on understanding of the effects of rotation rate upon the alternate shedding of vortices behind the cylinder and its relation to lift and drag forces exerted by the fluid on the cylinder.

There are various techniques for solving unsteady flows generated by impulsively accelerating bodies. In this work a non-rotating reference frame translating with the cylinder is employed. The temporal development of a two-dimensional viscous incompressible flow generated by a circular cylinder started impulsively into a combined (steady or unsteady) rotatory and rectilinear motion is investigated by solving a velocity/vorticity formulation of the Navier-Stokes equations. A new numerical approach is used in this work. This approach is based on an explicit finite-difference/pseudo-spectral technique, and uses a new implementation of the Biot-Savart law to produce accurate solutions to the governing equations [4].

The computations were performed over an extended variation of angular/rectilinear speed ratio $\alpha(t) = \Omega(t)a/u$ (where $\Omega(t)$ is the time-dependent angular speed) at a Reynolds number of 200, based on the cylinder diameter $2a$ and the magnitude U of the rectilinear velocity. In this model, the rectilinear velocity is fixed as a constant value while the angular velocity is treated as a control variable. Three kinds of rotation have been tested: (1) constant speed of rotation, (2) time-harmonic rotatory oscillation (i.e., $\alpha(t) = A\sin 2\pi f(t)$), and (3) time-periodic rotation (i.e, $\alpha(t) = A|\sin 2\pi ft|$).

Many flows of engineering interest (e.g. separating flows) produce the phenomena of vortex shedding and the associated structural response. The ability to tailor the wake of a bluff body could be used to reduce drag, increase mixing or heat transfer and enhanced combustion. In [4] we studied the fundamental problems associated with the development of the alternate shedding of vortices in the cylinder wake for several values of constant rotation. We tested the model against the experimental work of Coutanceau & Ménard and obtained excellent agreement. However, at higher rotation rates, our results indicate that vortex shedding does indeed occur, in contrast to the experimental conclusion of Coutanceau & Ménard. The issue of whether vortex shedding can be controlled by a cylinder rotation is of considerable practical interest from the standpoint of wake modification and the reduction of flow-induced vibrations.

In [5], [6] and [7] the development of flow patterns, histories of lift and drag are computed under a wide range of rotation with various amplitudes and frequencies. In fact, various formations of vortex streets were found to be intimately relative to the temporal evolution of the body forces. The implications of the resulting flow patterns were then used for enhancing the lift/drag ratio and delaying separation by using active control of the rotation rate. In [6] we presented numerical solutions of two specific flow control problems. The first problem is to find optimal rotation rate that maximizes the time-averaged lift-to-drag functional, and the second problem is to find optimal rotation rate that maximizes the total lift-to-drag functional. A complete discussion of all results may be found in [8].

In [9] we present results involving mathematical theory, numerical computations and laboratory experiments for optimal control problems associated with viscous flow past a cylinder. An existence theorem is given for the optimal control problem. This result uses an infinite dimensional Hamilton-Jacobi-Bellman equation to provide the feedback map. An experimental study into the use of suction/blowing slots at the cylinder boundary to prevent unsteady boundary layer separation is underway. Numerical computations were performed for the optimal control of time-averaged forces on a rotating cylinder utilizing rotation rate as a control parameter. In the computations, all of the optimal solutions are obtained by direct calculation. However, future effort should focus on the feedback control problem. This problem has not been solved.

The moving surface control mechanism was demonstrated to be intimately relevant to the vortex shedding process in the wake and to the development of the forces acting on the cylinder surface [10].

Further numerical investigation should focus on the implementation of a computational algorithm to calculate the optimal solution based on a direct solution of the necessary conditions. The tools developed here can be used to investigate fundamental questions regarding control of separated flows by using boundary control mechanisms. However, new computational algorithms need to be developed to solve the necessary conditions for the complete optimal control problem.

It has become clear that reduced models must be used in any practical feedback control design. Consequently, one must have a robust parameter identification algorithm in order to rapidly build and test potential models. Paper [11] is a first step in this direction.

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